AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2015WR018090

Key Point:

- GRACE Total Water Storage was extended to 1980 showing 50–100 km^3 depletions related to droughts

Supporting Information:

- Supporting Information S1

Correspondence to:
B. R. Scanlon,
bridget.scanlon@beg.utexas.edu

Citation:
Scanlon, B. R., Z. Zhang, R. C. Reedy, D. R. Pool, H. Save, D. Long, J. Chen, D. M. Wolock, B. D. Conway, and D. Winester (2015), Hydrologic implications of GRACE satellite data in the Colorado River Basin, *Water Resour. Res.*, *51*, 9891–9903, doi:10.1002/2015WR018090.

Received 10 SEP 2015
Accepted 27 NOV 2015
Accepted article online 8 DEC 2015
Published online 24 DEC 2015
Corrected 12 JAN 2016

This article was corrected on 12 JAN 2016. See the end of the full text for details.

Hydrologic implications of GRACE satellite data in the Colorado River Basin

Bridget R. Scanlon[1], Zizhan Zhang[1], Robert C. Reedy[1], Donald R. Pool[2], Himanshu Save[3], Di Long[4], Jianli Chen[3], David M. Wolock[5], Brian D. Conway[6], and Daniel Winester[7]

[1]Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA, [2]U.S. Geological Survey, Arizona Water Science Center, Tucson, Arizona, USA, [3]Center for Space Research, University of Texas at Austin, Austin, Texas, USA, [4]Department of Hydraulic Engineering, Tsinghua University, Beijing, China, [5]U.S. Geological Survey, Kansas Water Science Center, Lawrence, Kansas, USA, [6]Arizona Department of Water Resources, Phoenix, Arizona, USA, [7]USDOC - NOAA - National Geodetic Survey, Table Mountain Geophysical Observatory, Boulder, Colorado, USA

Abstract Use of GRACE (Gravity Recovery and Climate Experiment) satellites for assessing global water resources is rapidly expanding. Here we advance application of GRACE satellites by reconstructing long-term total water storage (TWS) changes from ground-based monitoring and modeling data. We applied the approach to the Colorado River Basin which has experienced multiyear intense droughts at decadal intervals. Estimated TWS declined by 94 km^3 during 1986–1990 and by 102 km^3 during 1998–2004, similar to the TWS depletion recorded by GRACE (47 km^3) during 2010–2013. Our analysis indicates that TWS depletion is dominated by reductions in surface reservoir and soil moisture storage in the upper Colorado basin with additional reductions in groundwater storage in the lower basin. Groundwater storage changes are controlled mostly by natural responses to wet and dry cycles and irrigation pumping outside of Colorado River delivery zones based on ground-based water level and gravity data. Water storage changes are controlled primarily by variable water inputs in response to wet and dry cycles rather than increasing water use. Surface reservoir storage buffers supply variability with current reservoir storage representing ~2.5 years of available water use. This study can be used as a template showing how to extend short-term GRACE TWS records and using all available data on storage components of TWS to interpret GRACE data, especially within the context of droughts.

1. Introduction

The Colorado River Basin (CRB, area 657,000 km^2) is a critical region providing water to ~40 million people in seven states [*U.S. Bureau of Reclamation (USBR)*, 2012] (Figure 1). Though the Colorado River water serves large populations outside of the basin, particularly Los Angeles, population within the basin is concentrated in the Lower CRB (LCRB: 8.6 million), mostly in the cities of Phoenix and Tucson (Table S2 in the Supporting Information). In contrast, only ~1 million people reside in the Upper CRB. Water from the basin is used to irrigate ~22,000 km^2 of land, within and outside the basin [*USBR*, 2012]. There is a spatial disconnect between water supply, with ~90% of streamflow generated in the UCRB, and water use, which is much higher in the LCRB [*USBR*, 2012]. Reservoir storage capacity is high (87 km^3), mostly (71%) in Lakes Powell and Mead, and represents almost five times the annual naturalized flow of the Colorado River at Lee's Ferry gage (18.3 km^3/yr; Figures S1 and S2 and Table S3). Water is over-allocated (20.3 km^3) in the basin; this is due in part to allocation levels having been set in 1922 during a period of above average flow relative to the current ~100 year average flow (section S1, Figure S2). Dry conditions since 2000 have resulted in average (naturalized) flow of 15 km^3/yr at Lee's Ferry and reservoir storage sharply declined from a peak of 69.2 km^3 (2000) to 42.4 km^3 (2004). Reservoir storage in 2014 represented 44% of reservoir capacity and 69% of long-term average storage, raising concerns about water reliability (section S1).

The Gravity Recovery and Climate Experiment (GRACE) satellites are increasingly being used to monitor changes in water storage in large basins globally. The area of the Colorado River Basin (CRB) makes it suitable for analysis using GRACE satellites, which requires a large footprint based on the elevation of the

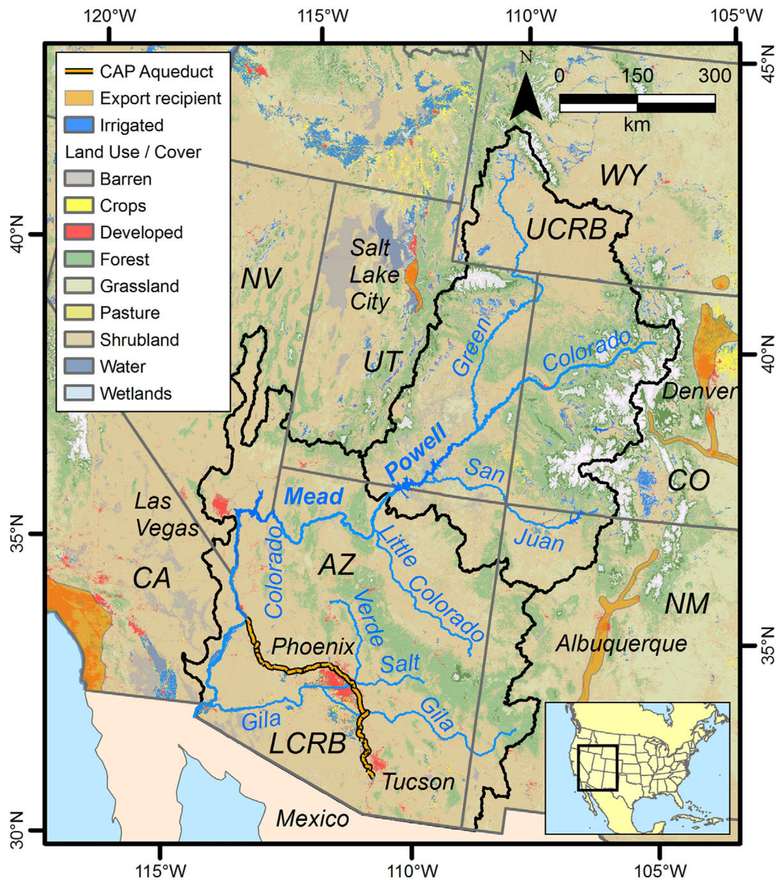

Figure 1. The Upper and Lower Colorado River Basins (UCRB, LCRB) outlined in black, and land use based on National Land Cover Data (2006). Land use percentages for each region are shown in Table S1. The main reservoirs (Powell and Mead) are shown and elevations above 2740 m (9000 ft) areas that regularly accumulate substantial snowpack are highlighted in light grey. Regions outside the CRB that receive exported water are highlighted: 0.93 km^3 exported out of UCRB to parts of Colorado, New Mexico, Utah, and Wyoming and 5.3 km^3 exported out of the LCRB to California.

satellites above land surface (current altitude 400 km, footprint area $\sim$200,000 km^2). GRACE satellites monitor temporal changes in Earth's gravity, which result primarily from redistribution of water in the land atmosphere system [*Wahr et al.*, 1998; *Tapley et al.*, 2004]. Changes in total water storage (ΔTWS) monitored by the GRACE satellites include changes in snow water storage (ΔSnWS), surface water reservoir storage (ΔRESS), soil moisture storage (ΔSMS), and groundwater storage (ΔGWS):

$$\Delta TWS = \Delta SnWS + \Delta RESS + \Delta SMS + \Delta GWS \tag{1}$$

These water storage changes are generally expressed in terms of water volume in a basin or as an equivalent water height (volume/area). Development of a new gridded GRACE product [*Landerer and Swenson*, 2012], with ΔTWS at 1°×1° resolution ($\sim$90 km in the basin), has greatly increased access to and applications of GRACE data in hydrology. Another approach for processing GRACE data, the Mascons approach, is being developed by a number of groups, including the Goddard Space Flight Center (GSFC) [*Luthcke et al.*, 2013], Jet Propulsion Lab (JPL) [*Watkins et al.*, 2015], and also the Univ. of Texas Center for Space Research [*Save et al.*, 2012, 2015] to provide unparalleled spatial resolution with lower uncertainties.

GRACE satellite data are widely used to assess GWS depletion [*Döll et al.*, 2014]. A recent application of GRACE to the CRB indicated that TWS declined by $\sim$65 km^3 from 2004 to 2013 (9 years; 7.2 km^3/yr) [*Castle et al.*, 2014]. Based on monitored SnWS, RESS changes, and simulated SMS from VIC, NOAH, and CLM land surface models (LSMs) in the Global Land Data Assimilation System (GLDAS), *Castle et al.* [2014] estimated the residual ΔGWS (from equation (1)) of $\sim$50 km^3 (5.6 km^3/yr), which they attributed to groundwater depletion. The large GWS depletions from the GRACE analysis in the UCRB are not consistent with the limited groundwater withdrawals (~0.5 km^3/yr, 2000–2010) [*Maupin et al*., 2014]. In addition, *Konikow* [2013] showed GWS declines in the LCRB up to 1980 and then a general reversal in this trend since 1980 attributed to importing water from the Colorado River to agricultural and urban areas through the Central Arizona Project (CAP) aqueduct [*Tillman and Leake*, 2010, Figure 1].

Water storage changes result from an imbalance between water inputs and outputs related to natural and anthropogenic effects:

$$\text{Input} - \text{Output} = \text{Change in storage} \tag{2}$$

What is the main driver of water storage depletion? Is it decreasing water inputs or supplies, or increasing water outputs that may be natural or anthropogenic, or a combination of both? In some cases, depletion may result from natural climate cycles from wet to dry periods. Also groundwater may be depleted by evapotranspiration (ET) by phreatophytes, or from pumping by humans, or both; however, the cause of depletion should be identified to better manage water resources. Because various storage components contribute to TWS changes monitored by GRACE, we need to determine which storage components are depleting: SnWS, RESS, SMS, or GWS? Each storage component may have a different temporal pattern of depletion based on the evolution of droughts and how water moves through the system.

The GRACE monitoring period is relatively short (2002-present); therefore, it is informative to consider GRACE data within the context of longer-term hydroclimatic records. Recent studies indicate that there has been a hydroclimatic shift in the CRB with decadal-scale variability since the mid-1970s, which is absent in records prior to the 1970s [*Nowak et al*., 2012]. Therefore, it is necessary to evaluate where the GRACE data fall within one of these wet-dry cycles when interpreting the hydrologic significance of the storage changes.

The objective of this study is to address the following questions:

1. What is the hydrologic significance of GRACE water storage changes within the context of longer term hydroclimatic trends in the CRB?
2. How can we use ground-based data to interpret GRACE TWS changes in terms of hydrologic components?

Details of the data sources and analyses conducted in this study are provided in section S2. The analysis included evaluation of the UCRB and LCRB and considers different GRACE products based on fundamentally different processing approaches (spherical harmonics and Mascons) (section S4). Long-term records of hydroclimatic parameters considering wet and dry cycles were examined to provide context for the recent GRACE data. A comprehensive evaluation of ground-based data was conducted to interpret GRACE TWS changes in terms of component storage changes. Data on RESS includes the two primary reservoirs (Powell and Mead) and other smaller reservoirs. SMS data were evaluated from land surface models (LSMs), including the Global and National Land Data Assimilation Systems (GLDAS and NLDAS). GWS changes were assessed from data on groundwater pumpage, groundwater level trends from ~2600 wells over the past three decades (section S3), and ground-based (GB) gravity data from ~200 gravity stations over the past 15 years (section S5). The analysis highlights the importance of using all available sources of data and long time scales to constrain interpretation of GRACE data.

2. Methods

Websites for sources of data used in this study are provided in section S2. Additional details on GRACE data sources and processing are described in section S4. This study used GRACE data based on two main processing approaches: (1) spherical harmonics (SH) and (2) Mascons (Mass Concentrations). The most widely used GRACE data are based on spherical harmonic (SH) solutions. GRACE TWS data based on SH solutions include the gridded products provided by NASA JPL TELLUS website and based on the SH solutions provided by the three processing centers, CSR, JPL, and GFZ. The data include monthly GRACE TWS data (2002–2015) from the latest release (RL05) at a grid resolution of 1° (~90 km). We also processed the GRACE SH data at the basin scale using CSR RL05 data for the UCRB and LCRB separately to compare with the aggregated gridded products. Processing of these data included truncation at 60°, destriping according to *Swenson and Wahr* [2006], and application of a fan filter at 250 km resolution [*Zhang et al*., 2009]. Uncertainties in the gridded and basin scale GRACE SH TWS data were estimated by applying GRACE processing

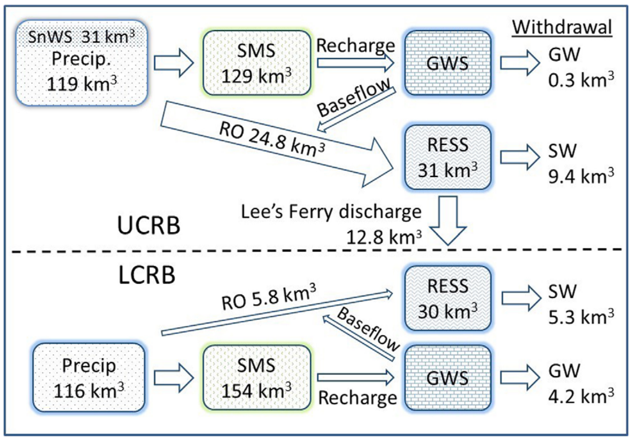

Figure 2. Schematic diagram of interrelationships between different water balance components in the Upper (UCRB) and Lower (LCRB) Colorado River Basin. Components include precipitation (Precip), which also includes snow water storage (SnWS), soil moisture storage (SMS), groundwater storage (GWS), reservoir storage (RESS), runoff (RO), and surface water discharge. Also shown are withdrawal volumes from groundwater (GW) and surface water (SW). Values represent either mean total (Precip, RO, discharge, and withdrawals), mean storage (SMS and RESS), or the mean maximum (SnWS) for 1980–2014 water years.

(truncation and filtering) to simulated SMS from LSMs and comparing with the raw data. Variability in TWS estimates based on different GRACE solutions provides an indication of uncertainties.

An alternative to the GRACE SH solutions is the CSR Mascons solutions that are considered to have higher signal-to-noise ratio, higher spatial resolution, and reduced error relative to SH solutions [*Watkins et al.*, 2015; *Save et al.*, 2012, 2015; *Rowlands et al.*, 2010]. In this study we used Mascons solutions based on CSR RL05 data up to 120° and constrained using Tikhonov regularization to reduce systematic errors (e.g., errors manifested as N-S stripes in the SH solutions) without reducing signal [*Save et al.*, 2012]. Additional advantages of the Mascons solutions are analysis based entirely on GRACE data without the need for other hydrologic model estimates (to correct for leakage), and minimal signal loss based on postfit residual analysis relative to GRACE K band range rate data; therefore, no requirement for signal restoration.

Development of GWS from groundwater level monitoring data is described in section S3. Details of ground-based gravity data processing are provided in section S5.

3. Results and Discussion

3.1. Spatial Variability in Mean Hydroclimatic Parameters

The UCRB and LCRB are climatically and hydrologically distinct. The CRB can be described in terms of water storages and connecting fluxes based on long-term mean annual data from 1980 to 2014 data (Figure 2). Precipitation is similar in the UCRB and LCRB (Figure S5). Seasonal distribution of precipitation is more uniform in the UCRB relative to the LCRB where summer precipitation is dominant related to the North American Monsoon (Figure S6). Snow is mostly restricted to the UCRB because of its higher elevation (Figure S3). The UCRB is the primary source of runoff, accounting for ~80% of the runoff in the basin, derived primarily from spring snowmelt (Figure S7). Reservoir storage (RESS) capacity is similar in the UCRB (43 km^3) and the LCRB (45 km^3) (Table S3), but is supplied primarily by runoff in the UCRB. Average storage in UCRB reservoirs is 31 km^3/yr, dominated by Lake Powell, with outflows from Lake Powell providing the primary input to Lake Mead in the LCRB (Figure 2). The two reservoirs have been managed jointly since 2007. Mean RESS in the CRB (61 km^3) averages ~3 times long-term (1906–2012) mean annual naturalized flow at Lee's Ferry gage (~18 km^3/yr, Figure S2). SMS, mostly in the upper 2 m, based on GLDAS and NLDAS LSMs averages ~129–154 km^3 in each basin. Recharge links SMS to GWS but quantitative recharge estimates are limited. The CRB is underlain by aquifers of sedimentary rocks in the UCRB and northern LCRB and mostly alluvial basin-fill aquifers (~80 mapped) in the lower LCRB (Figure S8). Water withdrawals are mostly from surface water in the UCRB and about half surface water in the LCRB (Figure 2).

3.2. Long-Term Climatic and Anthropogenic Drivers of Water Storage Changes

Variations in inputs are related to wet and dry cycles, with one major, multiyear drought approximately each decade, in the late 1970s, around 1990, early 2000s, and 2010s and intervening wet periods, primarily in the 1980s and 1990s (Figures 3, S9, and S10; Table S4). The ranking of precipitation over the entire record in the UCRB highlights the three droughts, with 1977 ranked as the driest year on record (first), 2002 second driest, and 2012 seventh driest (Figure S9a and Table S4). The wettest years are concentrated in the 1980s and 1990s (1997 first, 1995 second, 1986 fourth, and 1984 sixth). Precipitation trends in the LCRB are

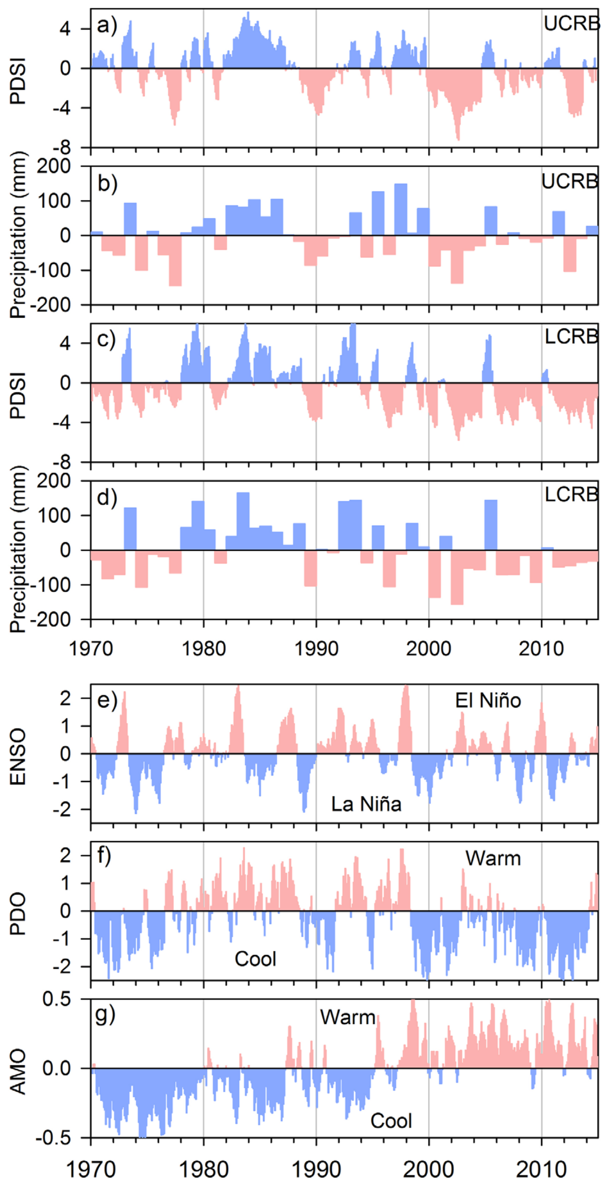

Figure 3. Palmer Drought Severity Index (PDSI) and annual total precipitation for the (a, b) Upper and (c, d) Lower Colorado River basins and global values for (e) El Niño Southern Oscillation (ENSO), (f) Pacific Decadal Oscillation (PDO), and the (g) Atlantic Multidecadal Oscillation (AMO) for the period 1970–2014. All values represent anomalies relative to the period average. PDSI based on spatially weighting output for climate divisions that comprise these basins. Data source is National Climatic Data Center (NCDC). Precipitation based on Prism (Prism Climate Group, http://www.prism.oregonstate.edu/). Positive values of PDSI correspond with wet periods and negative values with dry periods. The National Drought Monitor indicates that PDSI ranges from −1.0 to −2.0 correspond to abnormally dry, −2 to −3 moderate drought, −3 to −4 severe drought, −4 to −5 extreme drought, and < −5 exceptional drought (http://droughtmonitor.unl.edu/).

similar to those in the UCRB. Since 2000 there were only two anomalously wet years in the UCRB (2005 and 2011) and one in the LCRB (2005).

Drought indices are used to assess temporal variability in meteorological drought. The Palmer Drought Severity Index (PDSI) data in the UCRB show mostly drought conditions since 2000 preceded by wet conditions throughout much of the 1980s and 1990s (Figures 3a, S10a and S10b). In the UCRB, large negative PDSIs mark decadal interval droughts, including 1977, 1989–1991, 2000–2004, and 2012–2013. Large positive values of PDSI reflect major wet periods, extending over much of the 1980s (1978–1988) and 1990s (1993–1999) but were restricted to 2005 and 2011 within the past 15 years. Results from analysis of the 12 month Standardized Precipitation Index (SPI12) are similar to those from PDSI (Figures S10b and S10c). PDSI data for the LCRB show more continuous drought conditions since late 1995 with several short wet periods of a few months to a year (Figure 3c). The LCRB also shows severe drought around 1990 (October 1988 to June 1990), similar to the UCRB. Much of the 1980s and early 1990s have high values of PDSI, indicating wet periods.

It would be valuable to understand possible controls on these wet and dry periods. Previous studies indicate that climate teleconnections play an important role in controlling precipitation in the LCRB, with drought conditions associated with the cool phase of El Niño Southern Oscillation (negative ENSO, La Niña), cool phase of Pacific Decadal Oscillation (negative PDO), and warm phase of the Atlantic Multidecadal Oscillation (positive AMO), as seen in the drought during the early 2000s [*Quiring and Goodrich*, 2008] and during 2011–2012 (Figures 3e–3g and Figures S10g–S10i; Tables S5–S7). These findings are consistent with those of *McCabe et al.* [2004] for the western U.S. with drought related to negative PDO and positive AMO that may modulate ENSO teleconnections. The opposite conditions result in wet periods (warm phases of ENSO, El Niño) and PDO (positive PDO, 1976–1999) and cool phase of AMO (negative AMO, 1964–1994) resulting in wet winters throughout much of 1980s and early 1990s. Although there is no consistent relationship between wet and dry conditions and climate cycles in the UCRB [*Hidalgo and Dracup*, 2003], the severe drought in the early 2000s and also in 2012 correspond to cool phases of ENSO (La Niña) and PDO and warm phase of AMO, as in the LCRB. The phases of the long-term climate cycles (negative PDO and positive AMO) since ~2000 favor drought, as has been experienced in the CRB over this time with minimal wet years. Recent increases in ENSO and PDO suggest a warm phase for both indices in the near future that could result in increased winter precipitation.

Anthropogenic drivers of water storage change include water withdrawals, which are similar in the UCRB and LCRB (~10 km^3/yr) (Figures 2 and S11; Table S2). However, water is derived mostly from surface water (97%) in the UCRB and about half surface water in the LCRB. Total water withdrawals have decreased by 13% in the UCRB gradually since mid-1980s and by 24% in the LCRB since 1995. Reductions in GW withdrawals in the LCRB are attributed in part to the Central Arizona Project (CAP) which delivers up to ~1.5 km^3/yr to the Phoenix, Pinal, and Tucson Active Management Areas (Figure S12). Consumptive use and losses (CULs) are calculated by the U.S. Bureau of Reclamation (USBR) by subtracting return flows from withdrawals. CULs in the UCRB average about half of the 1922 allocation (5.1 km^3/yr out of 9.2 km^3/yr) whereas CULS in the LCRB Colorado River main stem approximately equal the allocation (~9.2 km^3/yr, 2003–2004); however, more than half of the LCRB withdrawal is exported to California (Figure S13 and Table S8b). Additional water is withdrawn from tributaries to the Colorado River (e.g., Gila and Virgin) and from groundwater in the LCRB (Table S8c). While the required allocations to the LCRB (9.2 km^3/yr) have been met each year by deliveries from Lake Powell, deliveries exceeded the allocated volumes in wet years, being much higher in the early 1980s, late 1990s, and 2011 amplifying water storage variations between wet and dry periods (Figure S14). The dominant water use is irrigation, accounting for ~60% of CUL in each basin (Figure S15). Evaporative losses average ~20% of the CUL in the UCRB and 13% in the LCRB (Figure S16 and Table S8).

3.3. Long-Term Trends in Water Storage

This section focuses primarily on droughts prior to GRACE monitoring. Long-term total water storage changes were estimated (TWSe) by summing monthly storage changes from ground-based monitoring (SnWS and RESS) and SMS modeling data for 1980–2014 (Figure 4 and Table S9). Changes in GWS were excluded in the UCRB because of minimal pumpage (~0.5 km^3/yr) and relatively stable GW level trends in the basin (Figures S17 and S18). GWS changes were included in TWSe in the LCRB based on groundwater level monitoring data. The only estimates of SMS trends are from GLDAS (coarse resolution, 1°, ~90 km) and NLDAS (fine resolution, 1/8°, ~11 km) LSMs (Figures S19 and S20). Differences in SMS between GLDAS and NLDAS LSMs are attributed in part to differences in precipitation input (Figure S21) and provide an indication of uncertainty in SMS trends. The following descriptions are based on GLDAS output because NLDAS output has been found to overestimate TWS changes from GRACE as discussed in section 3.4; however, trends based on both GLDAS and NLDAS are also provided in SI (Table S9).

3.3.1. Upper Colorado River Basin

Estimated TWS (TWSe) (SnWS + RESS + SMS) changes in the UCRB show decadal cycles with declines beginning prior to meteorological droughts around 1990, early 2000s, and in 2012–2013 (Figure 4a). There was a net decrease in TWSe of 38 km^3 over the entire period (1980–2014) (Table S9a). Although this volume seems large, 38 km^3 corresponds to 43 mm equivalent water depth after dividing by the basin area (~657,000 km^2). Rates of depletion of TWSe are similar for the 1990s drought (7.6 km^3/yr) and the early 2000s drought (7.1 km^3/yr); however, differences in drought periods result in varying total depletions from 31 km^3 for the 1986–1990 drought to 42 km^3 for the 1998–2004 drought (Tables 1 and S9a). TWSe recovered by 86% between the 1990s and early 2000s droughts in response to above average precipitation in the 1990s. There was little recovery after the 2000s drought with only two moderately wet years in 2005 and 2011 (Figure 3b).

SnWS was at the mean preceding and during the 1990s drought, but SnWS averaged 4.0 km^3 below the mean in 2000–2004 (Figure 4c). Spring snowmelt is earlier during drier years amplifying water losses (Figure S22). During wetter intervening periods, SnWS averaged ~3.8 km^3 (1983–1986) and 11.1 km^3 (1993–1999) above the mean.

SMS is the largest and most rapidly changing water storage component (Figure 4b). The onsets of SMS declines in the UCRB coincide with precipitation declines but lag SnWS and TWSe declines by several months to a year while SMS increases tend to coincide with precipitation and TWSe increases. Rates of SMS depletion vary from 5.2 km^3/yr between 1986 and 1990 (total 21.1 km^3) to 4.3 km^3/yr between 1998 and 2002

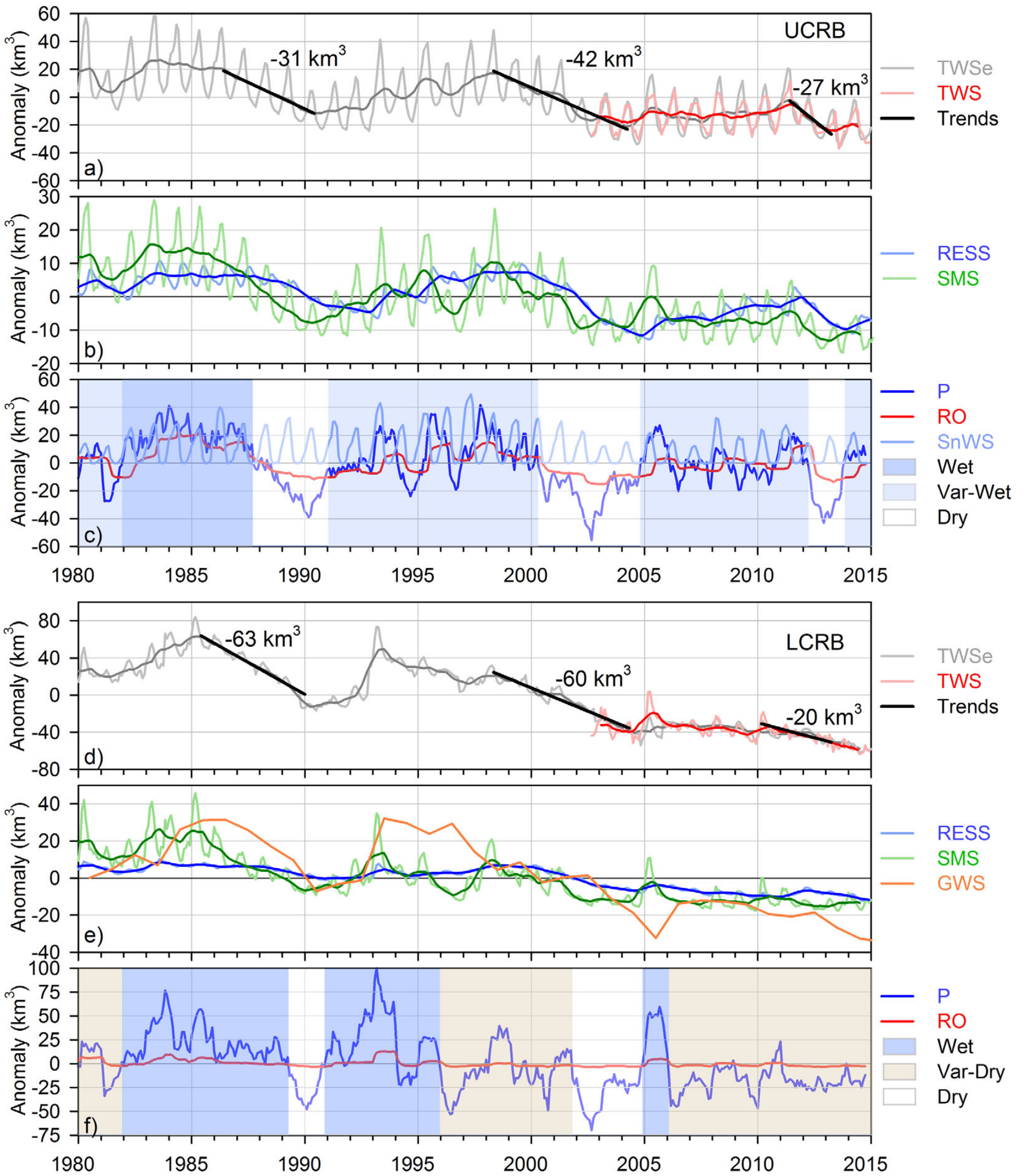

Figure 4. Time series of estimated total water storage (TWSe), GRACE total water storage (TWS), reservoir storage (RESS), soil moisture storage, (SMS from GLDAS), precipitation (P), runoff (RO), snow water storage (SnWS), and groundwater storage (GWS) in the (a–c) Upper (UCRB) and (d–f) Lower (LCRB) Colorado River Basin. Values represent anomalies relative to the 1980–2014 water year means. The centered 12 month moving averages (darker shades) and monthly values (lighter shades) are shown for TWSe, TWS, RESS, and SMS. The trailing 12 month sum anomaly is shown for P and RO. SnWS represents mean monthly values (not shown as an anomaly) and is based on SNOTEL data from 1980 to 2001 and SNODAS data from 2002 to 2014. GWS based on monitored data in the LCRB is shown as the water year mean. Trends shown in Figures 4a and 4d represent linear regressions of the monthly TWSe values for the periods shown. Shaded areas in Figures 4c and 4f qualitatively characterize periods as wet, variable to wet (Var-Wet), variable to dry (Var-Dry), or dry with respect to 1980–2014 mean precipitation. The TWS declines are represented as volumes (km^3) and can be converted to equivalent water depth by dividing by basin area (UCRB: 293,000 km^2; LCRB: 362,800 km^2). For example, 31 km^3 is equivalent to 105 mm of water in the UCRB.

(total 16.7 km^3) (Tables 1 and S9a). SMS partially recovered between 1993 and 1998 and between 2002 and 2004, remaining stable until 2011. Large variability in SMS within GLDAS LSMs, with standard deviation ranging from ∼50–70% of the mean provides an indication of uncertainties in SMS. This variability among LSMs exceeds the differences in mean SMS between GLDAS and NLDAS, e.g., 21 km^3 for GLDAS LSMs versus 25 km^3 for NLDAS LSMs for the 1990s drought (Table S9a).

Table 1. Period Intervals, Duration, Rates of Mean Storage Change, and Total Period Volumetric Changes for Different Water Storage Components During Three Multiyear Droughts in the Upper (UCRB) and Lower (LCRB) Colorado River Basin[a]

	UCRB				LCRB			
Component	Interval (MM/YY)	Duration (years)	Rate (km^3/yr)	Volume (km^3)	Interval (MM/YY)	Duration (years)	Rate (km^3/yr)	Volume (km^3)
1990s								
TWSe	05/86–05/90	4.0	−7.6	−30.9	05/85–12/89	4.6	−13.8	−63.2
SMS	05/86–05/90	4.0	−5.2	−21.1	05/85–12/89	4.6	−5.6	−25.5
RESS	03/89–11/92	3.7	−2.3	−8.7	01/88–08/91	3.6	−2.3	−8.2
GWS(obs)					1986–1990	4.0	−9.3	−37.3
2000s								
TWSe	04/98–03/04	5.9	−7.1	−41.9	04/98–04/04	6.0	−10.0	−60.3
SMS	04/98–03/02	3.9	−4.3	−16.7	04/98–07/02	4.3	−4.3	−18.4
RESS	01/00–11/04	4.8	−4.1	−19.8	12/99–07/04	4.6	−3.1	−14.1
GWS(obs)					2002–2005	3.0	−10.9	−32.7
2010s								
TWSe	05/11–03/13	1.8	−14.5	−26.7	02/10–03/13	3.1	−3.0	−9.2
TWS (GRACE)	05/11–03/13	1.8	−14.8	−27.2	02/10–03/13	3.1	−6.5	−20.0
SMS	05/11–03/13	1.8	−6.7	−12.3	02/10–03/13	3.1	−2.8	−8.5
RESS	11/11–11/13	2.0	−5.4	−10.8	12/11–11/14	2.9	−1.9	−5.5
GWS(est)	05/11–03/13	1.8	−0.26	−0.48	02/10–03/13	3.1	−4.8	−14.7
GWS(obs)					2012–2014	2.0	−7.1	−14.1

[a]More details are provided in Tables S9 and S13. TWSe: estimated Total Water Storage from sum of soil moisture storage (average SMS from GLDAS) and reservoir storage (RESS) in the UCRB and plus groundwater storage (GWS) in the LCRB, TWS: GRACE Total Water Storage, GWS(est): groundwater storage estimated as the residual from GRACE TWS minus SMS and RESS, GWS(obs): observed groundwater storage. To convert volume to equivalent water depth, use the area of the UCRB (293,900 km^2) and that of the LCRB (362,800 km^2).

Runoff links precipitation and snow pack to reservoir storage and is also impacted by SMS changes. Mean gaged runoff data in the UCRB follows similar decadal trends as precipitation, with minima during droughts (1989–1990, 2002, 2012–2013) and peaks in the intervening wet years (Figure 4c).

Reservoir storage (RESS) in the UCRB tends to change more gradually than other components with both RESS decreases and increases lagging those in precipitation, TWSe, SnWS, and SMS by a few months to 2.5 years (Figure 4b). Storage decreased rapidly by 8.7 km^3 between 1989 and 1992, almost three years after the onset of the TWSe decline (Table 1). RESS then partially recovered ($\sim$5.0 km^3 above the mean) by 1996 which persisted until late 1999. Between 2000 and late 2004, RESS declined by 19.8 km^3.

It is difficult to estimate the relative contributions of component storage changes to TWSe because of differences in timing of changes; however, comparing total changes suggests that the 1990s drought is dominated by SMS declines ($\sim$21 km^3) relative to RESS declines ($\sim$9 km^3) (Table 1). RESS and SMS contribute almost equally to TWSe declines in the 2000s drought.

3.3.2. Lower Colorado River Basin

Trends in TWSe in LCRB are generally similar to those in the UCRB, though declines tend to start 6 to 12 months earlier in the LCRB and recovery periods are more variable (Figure 4d; Tables 1 and S9b). The net decrease in TWSe from 1980 to 2014 is $\sim$103 km^3, 2.7 times greater than that in the UCRB. Rates of depletion in TWSe vary over the multiyear droughts (10.0–13.9 km^3/yr) resulting in similar total depletions of 63 km^3 in 1985–1989 and by 60 km^3 in 1998–2004 (Table 1). TWSe recovered substantially between these two droughts in response to high precipitation in 1992–1993, 1995, and 1999. Rates of SMS depletion varied from $\sim$5.6 km^3/yr in the 1985–1989 drought to $\sim$4.3 km^3/yr in the 1998–2002 drought. Variability in SMS among GLDAS LSMs in the LCRB is similar to those in the UCRB. RESS declined by 8.2 km^3 in the 1990s drought and $\sim$14.0 km^3 in the 2000s drought.

Trends in GWS were estimated from GW level data in different regions in the LCRB, focusing on unconfined aquifers, and weighted according to the area represented by each region (Figures 4e and 5; Figures S23 and S24). A uniform storage coefficient of 0.10 was used to convert GW level changes to GWS volumes. This value is considered a composite of most wells in shallow unconfined aquifers with storage coefficients of 0.10 to 0.15 and some wells in semiconfined or confined aquifers with storage coefficients $<$0.001. Uncertainties in storage coefficients should result in similar uncertainties in GWS because the two are linearly related. Future work will examine spatially distributed storage coefficients in the basin. The trends are

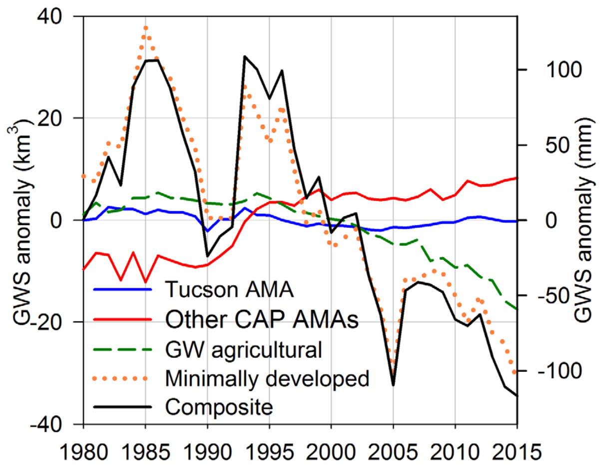

Figure 5. Arizona groundwater storage (GWS) anomalies for the contributing regions shown in Figure S23. Regional GWS volume changes were estimated as average GW level changes in wells multiplied by the unconfined aquifer areas in each region and by a 0.10 (uniform) storage coefficient. The right hand axis represents the equivalent water depth with respect to the entire area of Arizona, which closely approximates the LCRB area. The regions are the Active Management Area (AMAs) that receive Colorado River water imported by the Central Arizona Project (CAP) aqueduct, including the Tucson AMA (3% of area) and the Phoenix and Pinal AMAs combined (Other CAP AMAs, 7%), irrigated agricultural basins not receiving imported water (GW agricultural, 7%), and minimally developed regions (75%). The composite anomaly (Composite) thus represents the simple sum of these regional anomalies (92% of Arizona). Areas adjacent to the Colorado and Gila rivers (8% of area) were excluded. The storage coefficient used is considered reasonable because the composite trend is dominated by GW storage changes outside areas of intensive pumping where shallow unconfined aquifers represent the dominant water source and confined aquifer areas were not included in the analysis. Spatial variability in GW level trends at 5 year increments in the AMAs are shown in Figure S25 which are consistent with the composite trends. 2014 values are: Tucson AMA = −0.2 km^3, Other CAP AMA = +7.8 km^3, GW agricultural = −15.9 km^3, minimally developed = −24.3 km^3, Composite = −32.6 km^3.

dominated by GWS in minimally developed regions because they represent ~75% of the area. Area weighted GWS trends in the Active Management Areas (AMAs, Figure S3) are minimal (Tucson, 3% of area) or increasing (other CAP AMAs, 7% of area) (Figure 5) because of imports of Colorado River Water partially replacing GW pumpage and increased artificial recharge in spreading basins (Figure S12). Declines in GWS are focused in irrigated agricultural areas (7% of area) that do not have access to Colorado River or other significant surface-water sources (Figure 5). The composite GWS increases over the entire area in the early 1980s and 1990s reflect mostly natural increases in GWS in minimally developed regions in response to anomalously high precipitation and natural recharge. The composite GWS declines during the 1986–1990 drought (37.3 km^3) reflect depletion caused by GW discharge to supply irrigated agricultural areas, streams (baseflow), and riparian areas (ET), and reduced recharge. GWS recovered from the ~1990s drought in 1992–1993 (Figure 4e). The effects of the water pulse from the wet period in the early to mid-1990s moved through the system, as shown by the decline in GWS from 1996 to 1998, followed by a period of relative stability through 2002. GWS depletion during 2002–2005 lags depletion in other water budget components in response to the drought in the early 2000s and totals 32.7 km^3. The composite GWS trend primarily reflects responses to wet and dry climate cycles representing most of the area. Trends in GW levels in AMAs (Figure S25) are generally consistent with the time series analysis.

Although the timing of water storage depletions varies among the components, GWS depletion exceeds SMS depletion by a factor of ~1.5 and exceeds RESS by a factor of ~4.5 in the 1990s drought (Table 1). GWS depletion in the 2000s drought exceeds RESS and SMS by about a factor of 2 in the 2000s drought.

3.4. GRACE Total Water Storage Changes

The GRACE monitoring period (2002–2015) begins towards the end of the extreme drought in the late 1990s to early 2000s. This section focuses on CSR Mascons data because of its higher spatial resolution, increased signal-to-noise ratio, reduced leakage, and processing based entirely on GRACE data (section S4). Results from other processing approaches are tabulated in the SI and are discussed under uncertainties in TWS. Gridded output from JPL Tellus based on data from the three processing centers (CSR, JPL, and GFZ) provide generally similar results (Figure S26). Basin scale analysis using CSR data also results in TWS similar to the gridded output (Figure S27), and consistent with the findings of *Landerer and Swenson* [2012]. Variations and trends in TWS from CSR Mascons and the gridded data are shown in Figure S28.

In the UCRB, TWS increases in 2005, remains relatively stable with interannual fluctuations until it increases again in 2011 followed by a sharp decline in mid-2011 to early 2013 with a slight recovery thereafter (Figures 4a and S28). The TWS increases in 2005 and 2011 reflect storage increases in response to elevated precipitation. TWS declined sharply by 27 km^3 (CSR Mascons) in the recent drought (May 2011 to March 2013)

(Table 1). The TWS decline varies with different GRACE products and is lowest for CSR Mascons (27 km^3) and highest for TELLUS CSR and JPL gridded output (37 km^3) (Table S12). These differences in TWS may be related to lower leakage from surrounding areas for CSR Mascons relative to other products because of higher spatial resolution of CSR Mascons and potential leakage from the extreme drought in California to the west. This TWS decline in CSR Mascons is similar to the TWSe decline that excludes GWS changes (27 km^3/yr; Table 1), indicating that GWS changes should have a negligible impact on TWS in the UCRB.

SnWS in the UCRB increased in 2005 and 2011 and decreased in 2012 followed by slight recovery (Figure 4c). RESS in the UCRB gradually increased from a minimum in 2004 (-11 km^3) to a peak in late 2011 (2 km^3) (Figure 4b). RESS declined by 10.8 km^3 during the drought (November 2011 to November 2013) (Table 1) and is followed by a slight recovery. Trends in SMS are dominated by increases in response to elevated precipitation in 2005 and 2011 and relatively stable during the intervening period (Figure 4b). SMS from GLDAS declined by 12.3 km^3 between May 2011 and March 2013 followed by a slight recovery. Therefore, the TWS and TWSe declines in 2011–2013 can be explained by almost equal contributions from RESS and SMS. The residual water storage change, after subtraction of SnWS, RESS, and SMS, (0.48 km^3) may be related to deep SMS and/or GWS, most likely related to natural variations in response to climate variability (Table 1).

In the LCRB, the primary trends in TWS are an increase in 2005 followed by a gradual decrease to 2009, a slight increase in 2010, and rapid decrease through 2014 (Figures 4d and S28c). Increases in NLDAS SMS exceed those in TWS, indicating overestimation of SMS by NLDAS models whereas increases in average SMS from GLDAS LSMs are lower (Figure S29). This is the primary reason we have focused on GLDAS output. Partial reduction in SMS after 2005 is attributed to losses related to ET (corresponding to $\sim$50% of SMS in LSMs). The large depletion in 2010 in the LCRB occurs a year earlier than that in the UCRB because of high precipitation in the UCRB in 2011. Variations in TWS around 2005 are dominated by SMS changes. Differences in GLDAS and NLDAS SMS changes reflect uncertainties in simulated SMS changes.

The decline in GRACE TWS in the LCRB from February 2010 to March 2013 totaled 20.0 km^3 based on CSR Mascons solutions (Figure 4d and Table 1). TWS declines were greater for other GRACE products, ranging from 27.6 to 33.1 km^3 that again may be related to leakage from surrounding regions (Table S12). SMS depletion over this period totaled 8.5 km^3 based on GLDAS. SMS declines based on NLDAS are again much greater (18 km^3) (Table S9b). Decline in RESS, mostly Lake Mead, totaled 5.5 km^3. The residual depletion could be attributed to deep SMS or GWS, totaling 14.7 km^3; however, there are large uncertainties in this residual because of TWS differences among different GRACE products and variability in SMS among GLDAS and NLDAS LSMs. Estimated residuals range from minima of 5–11 km^3 based on low GRACE TWS (CSR Mascons) and high SMS (NLDAS and GLDAS NOAH) to maxima of 19–31 km^3 based on high GRACE TWS (Tellus CSR gridded) and low SMS (NLDAS VIC and GLDAS CLM)(Table S13b). The estimate of GWS changes from water level data is $\sim$14 km^3 (Table 1 and Figure 5). About half of the GWS depletion is related to irrigation pumpage in areas outside of Colorado River deliveries and the remaining is in minimally developed areas with natural responses of GWS to drought. However, the number of wells used in the time series decreased sharply in recent years, reducing the reliability of the storage changes (Figure S24c). The time-series trends in storage change are also consistent with GW-level trends using data within the AMAs (Figure S25).

3.5. Ground-Based Gravity Data

Ground-based (GB) gravity also tracks changes in subsurface water storage, including SMS and GWS, similar to GRACE satellites. Synoptic surveys were conducted in the Phoenix and Tucson AMAs (Figure S4). Details of the analysis of the GB gravity data are provided in section S5.

In the Phoenix AMA, results of synoptic surveys show a gradual increase in water storage, totaling $\sim$2.4 km^3 between 2002 and 2009 (0.34 km^3/yr; Figure 6 and Table S14). This gradual trend is interrupted by a sharp increase and decrease around 2005, which is attributed to SMS, because the survey was completed in spring 2005 immediately following a wet winter. The partial decline after 2005 is attributed to ET of soil moisture. Attribution of water storage changes around 2005 to SMS is supported by the GW level monitoring data, which do not show a rapid increase or decrease at this time (Figure 5). Increases in GB gravity after this time are attributed to drainage below the root zone in response to wet conditions in 2005 plus managed aquifer recharge of Colorado River water in the Phoenix AMA. This trend is supported by GW level monitoring data (Figure 5).

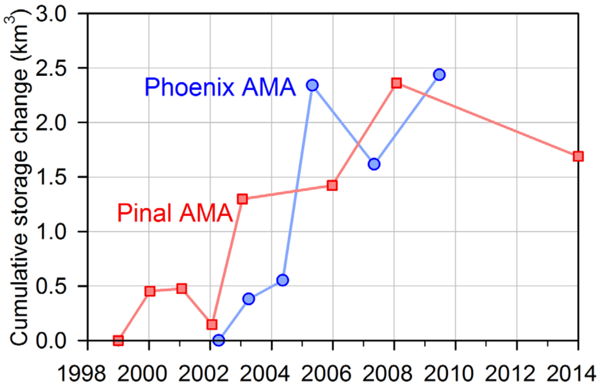

Figure 6. Cumulative changes in water storage based on synoptic gravity surveys in the Phoenix and Pinal Active Management Areas (AMAs). For location of the AMAs, see Figure S3.

In the Pinal AMA, water storage from the GB-gravity surveys follows a similar trend to those in the Phoenix AMA between 2002 and 2008 without the increase related to SMS in 2005 because of the difference in timing of the synoptic surveys (Figure 6). The long-term increase of ~2.4 km^3 over this time (0.3 km^3/yr) is likely derived from two sources, (1) incidental recharge of excess irrigation water imported from the Colorado River through the CAP aqueduct and (2) recovery of preexisting regional cones of depression through redistribution of water stored in adjacent areas. The final survey in 2014 suggests a reduction in water storage of 1.7 km^3 (0.11 km^3/yr) since the previous survey in 2008. The storage reduction is consistent with the increase in number of wells showing declining GW levels in 2010–2014 (Figure S25 and Table S11).

3.6. Implications for Water Resources

The primary advantages of GRACE satellite data for water resources assessment are the availability of monthly TWS changes over large basins globally providing regional estimates of the response of water storage to climate and anthropogenic drivers. GRACE satellite gravimetry is relatively young; therefore, processing GRACE data is continually improving. The CSR Mascons approach represents significant improvements over traditional processing in terms of spatial resolution at the basin scale, reduced leakage effects, checking against raw data for signal losses, and reliance on GRACE data alone (section S4). While the various GRACE products show similar trends in TWS, the main difference is the magnitude of the trends. Variability in the outputs of the different products provide an estimate of the uncertainties in the magnitudes of TWS trends.

Disaggregating TWS data into the different water budget components, particularly subsurface storage into SMS and GWS changes, is problematic because of the general lack of ground-based monitoring of SMS in most regions and large uncertainties in simulated SMS in LSMs. This study emphasizes the differences in SMS in LSMs within and between GLDAS and NLDAS. Variations in SMS among the different LSMs within GLDAS are large, underscoring the problems with partitioning water at the land surface among ET, runoff, and drainage. These LSMs were originally designed to provide feedback to atmospheric processes, not focusing specifically on hydrologic processes. The new NASA SMAP (Soil Moisture Active Passive, http://smap.jpl.nasa.gov/) mission should help improve estimates of SMS in the future. In addition, we recommend ground-based monitoring networks be installed in more regions to increase *in situ* observations of SMS. Analysis of GW level data in the CRB suggests that trends in GWS may be dominated by responses in minimally developed regions to wet and dry climate cycles and GW pumpage in areas without access to Colorado River water. These trends highlight the importance of Colorado deliveries for conjunctive use of groundwater and surface water and managed aquifer recharge to enhance sustainable GW development. GWS estimates derived from evaluation of GW level data are subject to large (as much as an order of magnitude or more) uncertainties in storage coefficients and will be evaluated in more detail in future studies. Because of uncertainties in both satellite and ground-based data, it is critical to use all available data to constrain uncertainties in estimated water budget components.

The other issue with the GRACE data is the limited time series (2002–2015). Extrapolating the data backward in time using monitoring and modeling data provides longer-term context for the GRACE data. The estimated TWS data show that the CRB has been subjected to intense droughts, similar to the recent droughts, at approximately decadal intervals in the past. This study indicates that the dominant driver in the CRB system is natural variations in water inputs in response to climatic forcing, as shown by variations in naturalized discharge at Lee's Ferry gage (Figure 7). In contrast, anthropogenic water use over the past few decades has changed gradually. However, past water use may not reflect true water demand because of lack of access to water in some regions. Comparing current RESS with water use indicates that there is an

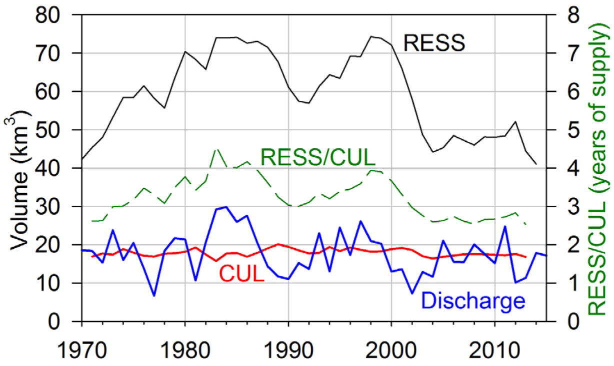

Figure 7. Annual total water consumption (CUL), naturalized Colorado River discharge at Lee's Ferry, reservoir storage (RESS) and RESS/CUL. Consumption is based on USBR Consumptive Uses and Losses (CUL) reports for the Upper (1971–2013) and Lower (1971–2005) Colorado River Basins. LCRB annual total water use values for 2006–2013 were estimated from the 2000–2005 mean (12.5 km^3/yr). Total reservoir storage in the Colorado River Basin was historically equal to 2.4–4.6 years of consumption (mean 3.2 years).

estimated 2.5 years of water storage remaining in the reservoirs. Variable water supplies related to wet and dry periods emphasize the heavy reliance on wet periods to replenish the system. Management of GWS is also heavily reliant on deliveries of Colorado River water to the AMAs. However, Arizona has junior water rights to Colorado River water relative to California and is therefore vulnerable to future potential shortages in deliveries. While TWS depletion rates during droughts have been fairly similar over time, the big difference with the recent droughts is the general lack of recovery because of minimal anomalously wet years compared to the wet 1980s and 1990s. Teleconnections, particularly AMO and PDO, have not been favorably aligned to promote wet conditions since the late 1990s and may explain the long-term climate cycles. Precipitation and particularly snow in the UCRB is critical because 80% of runoff in the CRB is generated in the UCRB.

Variability in water supplies results in water use exceeding water supplies during droughts (Figure 7). The primary approach for dealing with variability in water supplies is storing water to buffer the supply demand inequities. Exports to Mexico generally exceed the required allocation (1.8 km^3), particularly in the early to mid-1980s, 12–21 km^3 (Table S8b) suggesting that additional water might be stored in the CRB if it had additional capacity. Reservoir storage in the CRB averaged ~55 km^3 (1970–2014), ~3 times average annual naturalized flow in the river. Another approach is storing water in aquifers, either directly through managed aquifer recharge using spreading basins or wells or indirectly by substituting Colorado River water for groundwater in active management areas in Phoenix and Tucson. The Central Arizona Project transports up to ~1.5 km^3/yr from the Colorado River to south-central Arizona for irrigation and groundwater recharge. Supply and demand management plans for the basin forecast increasing storage in aquifers in the future (USBR, 2012). Other approaches to managing disconnects between supplies and demands include transferring water among different sectors, as seen in the reduction of irrigated agricultural water use and increase in urban water use in the LCRB in the past few decades (Figure S33).

Comprehensive evaluation of water resources in the CRB by combining GRACE satellite data, LSMs, and ground based measurements, advances our understanding of spatiotemporal variability in water resources in response to hydroclimatic and anthropogenic drivers. The importance of wet and dry cycles in controlling water supplies underscores the need for additional research in the processes controlling these cycles, particularly in the UCRB which is the primary source of runoff in the basin. Water storage plays a key role in buffering imbalances between water supplies and demands during these climate extremes. GRACE data are valuable for monitoring changes in TWS; however, disaggregating TWS into component storages requires improved data on SMS, a major gap that needs to be filled.

4. Conclusions

The Upper and Lower Colorado River basins are hydrologically distinct with 80% of runoff generated in the UCRB supplying reservoir storage primarily in Lake Powell and much greater water use in the LCRB and exports to California. The Basin has been subjected to multiyear intense droughts at approximately decadal intervals in the late 1970s, around 1990, early 2000s, and 2010s with wet periods mostly in the 1980s and 1990s as shown by PDSI. TWS was estimated (TWSe) back to 1980 by summing SnWS, RESS, and SMS in the UCRB plus GWS in the LCRB. In the UCRB TWSe declined by 31 km^3 from 1986 to 1990 and by 42 km^3 in 1998 to 2004 droughts. TWSe depletions are dominated by SMS and RESS. In the LCRB TWSe declined by

$\sim$60 km^3 for the 1990s and 2000s droughts and is dominated by GWS and SMS in the late 1980s and by GWS followed by RESS and SMS in the 2000s drought. GRACE data show variable trends in TWS throughout the 2000s followed by depletion of 27 km^3 in 2011–2013 in the UCRB and 20 km^3 in 2010–2013 in the LCRB. Depletion in the UCRB can be explained mostly by RESS and SMS declines. In the LCRB subtraction of SMS and RESS components from TWS results in a residual of 15 km^3 that is attributed to GWS and is similar to GWS declines derived from GW level monitoring data (14 km^3). Uncertainties in the residual are large, ranging from 5 to 31 km^3 based on different combinations of GRACE products and SMS from various LSMs. Ground-based gravity data show increases in water storage of 2.4 km^3 in the LCRB (2002–2009) in the Phoenix Active Management Area and by 2.4 km^3 in the Pinal AMA further south consistent with GW level monitoring data and increases in TWS derived from GRACE data during this time. Regional analysis of GW level data indicate that GWS changes in the LCRB are dominated by variations in precipitation during wet and dry periods and irrigation pumpage in areas that do not receive water from the Colorado River. The CRB is dominated by variable water supplies in response to wet and dry periods whereas water use has been relatively stable. Reservoir storage is used to buffer variability in supplies with an estimated $\sim$2.5 years of storage remaining based on current levels of water use. Water storage has expanded from surface reservoirs to aquifer storage through managed aquifer recharge within the past two decades. This study emphasizes the importance of placing GRACE TWS changes in context of longer term hydroclimatic records and using modeling and ground-based monitoring data to isolate different components of TWS from GRACE.

Acknowledgments
We acknowledge funding for this study from the Jackson School of Geosciences, University of Texas at Austin. We are very grateful for discussions with Ken Nowak at U.S. Bureau of Reclamation. We acknowledge the following individuals who provided data for this study: U.S. Bureau of Reclamation, Jesus Hernandez, Timothy Miller, Noe Santos, and Alan Harrison; Bureau of Indian Affairs, Augustine Fisher; U.S. Army Corps of Engineers, Jason Lee; and Arizona Department of Water Resources Central Arizona Project, Ken Seasholes.

References

Castle, S. L., B. F. Thomas, J. T. Reager, M. Rodell, S. C. Swenson, and J. S. Famiglietti (2014), Groundwater depletion during drought threatens future water security of the Colorado River Basin, *Geophys. Res. Lett.*, *41*, 5904–5911, doi:10.1002/2014GL061055.

Döll, P., H. Mueller Schmied, C. Schuh, F. T. Portmann, and A. Eicker (2014), Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites, *Water Resour. Res.*, *50*, 5698–5720, doi:10.1002/2014WR015595.

Hidalgo, H. G., and J. A. Dracup (2003), ENSO and PDO effects on hydroclimatic variations of the Upper Colorado River basin, *J. Hydrometeorol.*, *4*(1), 5–23.

Konikow, L. (2013), Groundwater Depletion in the United States (1900-2008), *U.S. Geol. Surv. Sci. Invest. Rep., 2013–5079*, 63 pp.

Landerer, F. W., and S. C. Swenson (2012), Accuracy of scaled GRACE terrestrial water storage estimates, *Water Resour. Res.*, *48*, W04531, doi:10.1029/2011WR011453.

Luthcke, S. B., T. J. Sabaka, B. D. Loomis, A. A. Arendt, J. J. McCarthy, and J. Camp (2013), Antarctica, Greenland and Gulf of Alaska land-ice evolution from an iterated GRACE global mascon solution, *J. Glaciol.*, *59*(216), 613–631.

Maupin, M. A., J. F. Kenny, S. S. Hutson, J. K. Lovelace, N. L. Barber, and K. S. Linsey (2014), Estimated use of water in the United States in 2010, *U.S. Geol. Surv. Circ., 1405*, 56 pp.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004), Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, *Proc. Natl. Acad. Sci. U. S. A.*, *101*(12), 4136–4141.

Nowak, K., M. Hoerling, B. Rajagopalan, and E. Zagona (2012), Colorado River Basin hydroclimatic variability, *J. Clim.*, *25*(12), 4389–4403.

Quiring, S. M., and G. B. Goodrich (2008), Nature and causes of the 2002 to 2004 drought in the southwestern United States compared with the historic 1953 to 1957 drought, *Clim. Res.*, *36*(1), 41–52.

Rowlands, D. D., S. B. Luthcke, J. J. McCarthy, S. M. Klosko, D. S. Chinn, F. G. Lemoine, J. P. Boy, and T. J. Sabaka (2010), Global mass flux solutions from GRACE: A comparison of parameter estimation strategies-Mass concentrations versus Stokes coefficients, *J. Geophys. Res.*, *115*, B01403, doi:10.1029/2009JB006546.

Save, H., S. Bettadpur, and B. D. Tapley (2012), Reducing errors in the GRACE gravity solutions using regularization, *J. Geod.*, *86*(9), 695–711.

Save, H., S. Bettadpur, and B. D. Tapley (2015), Evaluation of global equal-area mass grid solutions from GRACE, paper presented at European Geosciences Union General Assembly, Vienna.

Swenson, S., and J. Wahr (2006), Post-processing removal of correlated errors in GRACE data, *Geophys. Res. Lett.*, *33*, L08402, doi:10.1029/2005GL025285.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins (2004), GRACE measurements of mass variability in the Earth system, *Science*, *305*(5683), 503–505.

Tillman, F. D., and S. A. Leake (2010), Trends in groundwater levels in wells in the active management areas of Arizona, USA, *Hydrogeol. J.*, *18*(6), 1515–1524.

U.S. Bureau of Reclamation (USBR) (2012), Colorado River Basin water supply and demand study, study report, U.S. Dep. of Inter.

Wahr, J., M. Molenar, and F. Bryan (1998), Time variability of the earth's gravity field: Hydrologic and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, *103*, 30,205-30,230.

Watkins, M. M., D. N. Wiese, D.-N. Yuan, C. Boening, and F. W. Landerer (2015), Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons, *J. Geophys. Res. Solid Earth*, *120*, 2648–2671, doi:10.1002/2014JB011547.

Zhang, Z.-Z., B. F. Chao, Y. Lu, and H.-T. Hsu (2009), An effective filtering for GRACE time-variable gravity: Fan filter, *Geophys. Res. Lett.*, *36*, L17311, doi:10.1029/2009GL039459.

Erratum

In Table 1, incorrect numbers were present in the column "Volume (km^3)" in the rows "TWSe" under subheading "1990s" and "2000s." These numbers have since been corrected and this article should be considered the authoritative version of record.